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DESIGN AND PERFORMANCE OF PARAMETRIC SONAR SYSTEMS

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24 September 1975

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PREFACE

This study was performed under NUSC Project No. A-614-15, "Parametric Sonar Echo Ranging System," Principal Investigator — W. L. Konrad (Code TD124), and Navy Subproject and Task No. SF 11 121 706-17442/ 16702, Program Manager J. Neely (NAVSEA 06H1-1).

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A brief non-mathematical explanation of the difference frequency generation and beamforming process is followed by a step-by-step design procedure using the Mellen-Moffett parametric source model. The relative merits of projector feed with a single driver supplying both primary frequencies to the projector as opposed to the "checkerboard" technique are discussed. Distortion in both the parametric source

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20. ABSTRACT

and in receiving systems used in measurements is considered with suggestions on how these problems can be minimized. Applications of the parametric array to communications, echo ranging, and sub-bottom profiling are mentioned, and salient performances from tests of practical sources are listed. Finally, brief discussions of the results obtained from a cavitating, parametric source and from a parametric receiving array are given.

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INTRODUCTION

Conventional models of underwater acoustic behavior assume that signals propagate without modifications other than linear ones such as spreading, absorption, and scattering. A more complete model, however, takes into account the nonlinear effects of the medium. In nonlinear propagation, increases in speed caused by pressure changes over the waveform result in noticeable distortion. At a distance from a sinusoidal source, this distortion can result in a well-developed sawtooth wave.

The use of the medium's nonlinearity to generate intermodulation products when two or more frequencies are mixed is especially interesting and valuable. Of these intermodulation products, which include the sum and difference of two frequencies mixed in the medium, the difference frequency has properties of greater interest for underwater applications. Parametric sources generate a difference frequency by driving a transducer at two closely spaced frequencies.

The advantages of parametric sources include higher directivity than achievable with direct radiation, absence of sidelobe structure, and an inherent broadband capability.

Figure 1 illustrates the process of difference-frequency generation. The distortion of the primary frequencies results in envelope distortion, which is responsible for the generation of the difference frequency. If the generation function is separated from the spatial effects, the source level of the difference frequency is proportional to the square of the ratio of the difference frequency, f, to the mean primary frequency, f_o.

This proportion follows because a single cycle of the primary frequency is constrained to distort, or move forward, by an amount that is limited by the length of the cycle. Therefore, greater envelope distortion can be obtained when only a few cycles of the primary frequency are contained in each envelope section: the higher the difference frequency in a given source, the greater will be the available energy at the difference frequency. The spatial effects are

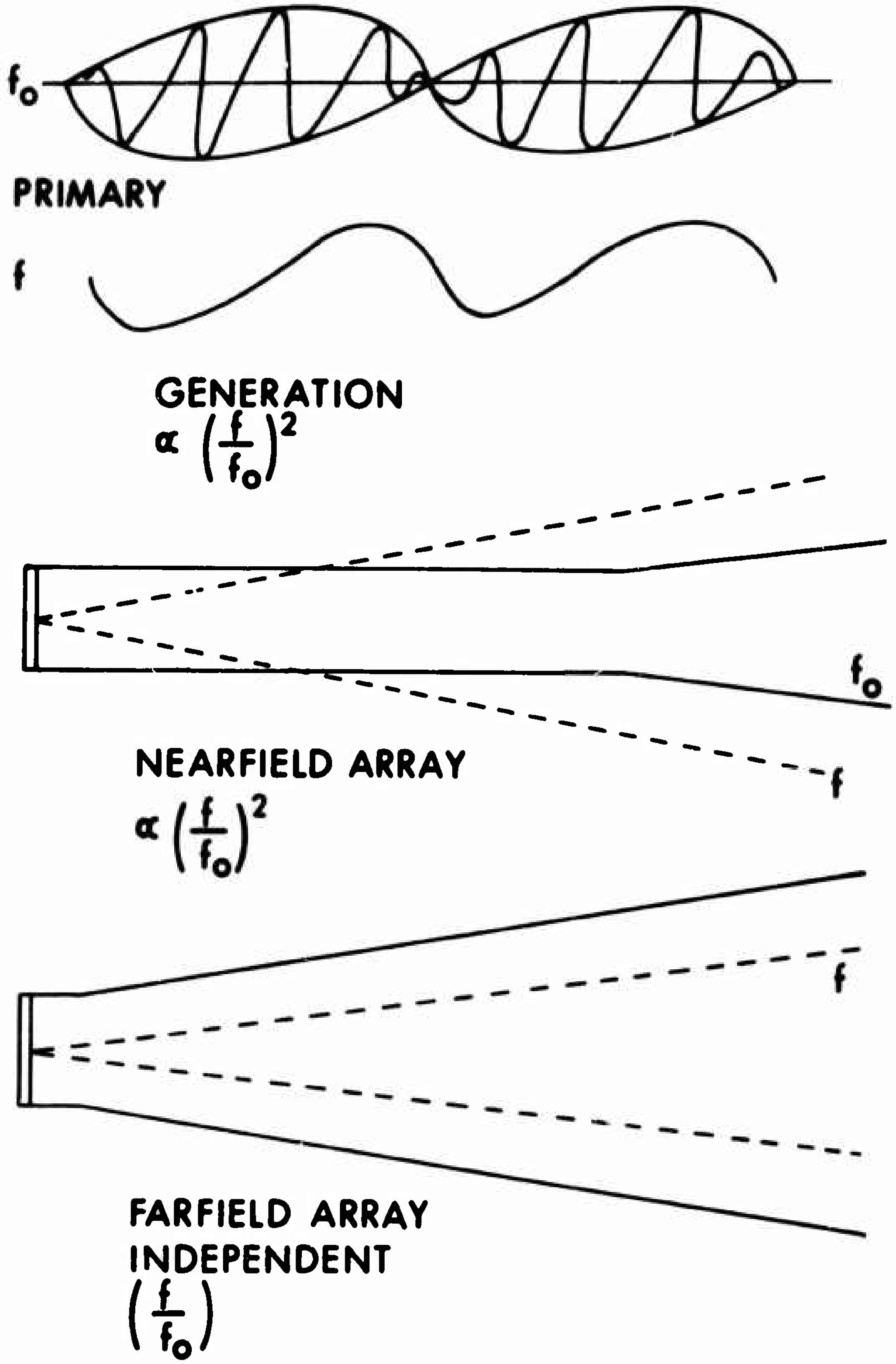

Figure 1. Physical Model of Difference-Frequency Generation

shown for both the nearfield source, where most of the difference frequency is generated in the nearfield of the primary frequencies; and for the farfield source, where most of the generation occurs in the farfield of the primaries. In the nearfield case, inasmuch as the difference-frequency energy escapes from the array at a distance proportional to the square of the difference frequency, an additional $(f/f_o)^2$ dependence occurs, and the source level of the difference frequency in the farfield becomes proportional to $(f/f_o)^4$. In the case of the farfield array, the difference-frequency source level is a function of the $(f/f_o)^2$ generation dependence only. Types of parametric sources span the range from nearfield to farfield, and hence the dependence upon the ratio of difference to primary frequency can be anywhere between $(f/f_o)^4$ and $(f/f_o)^2$.

PARAMETRIC SOURCE DESIGN

DESIGN USING THE MELLEN-MOFFETT MODEL

The Mellen-Moffett model[1] has been reduced to a set of design curves to permit rapid calculation of the essential characteristics of the difference frequency array. Curves for a stepdown ratio (f_o/f) of 10 are shown in figures 2 and 3. The term f_o is the mean primary frequency and f is the difference frequency, α is the small signal absorption at f_o in decibels per unit distance, and R_o, defined as projector area divided by the primary wavelength, is the primary collimation distance in the same length unit. L^* is the scaled primary frequency in dB/1 μPam -kHz.

The following example will illustrate the use of these curves. Consider a transducer system with the following parameters:

Projector diameter	0.9 m
Mean primary frequency f_o	65 kHz
Projector power input for each frequency	5 kW
Primary source level LSP for each frequency	246 dB//1 μPam
Scaled source level L^* for each frequency	282 dB//1 μPam -kHz.
Primary collimation distance R_o	28 m
αR_o (α = 0.022 dB/m)	0.6 dB
Primary directivity index NDIP	42 dB
Primary beamwidth 3 dB points	1.5°

Referring to figure 2, we enter the curve at the abscissa with an L^* of 282 dB//1 μPam-kHz. Reflecting off the αR_o = 0.6 curve, we read a

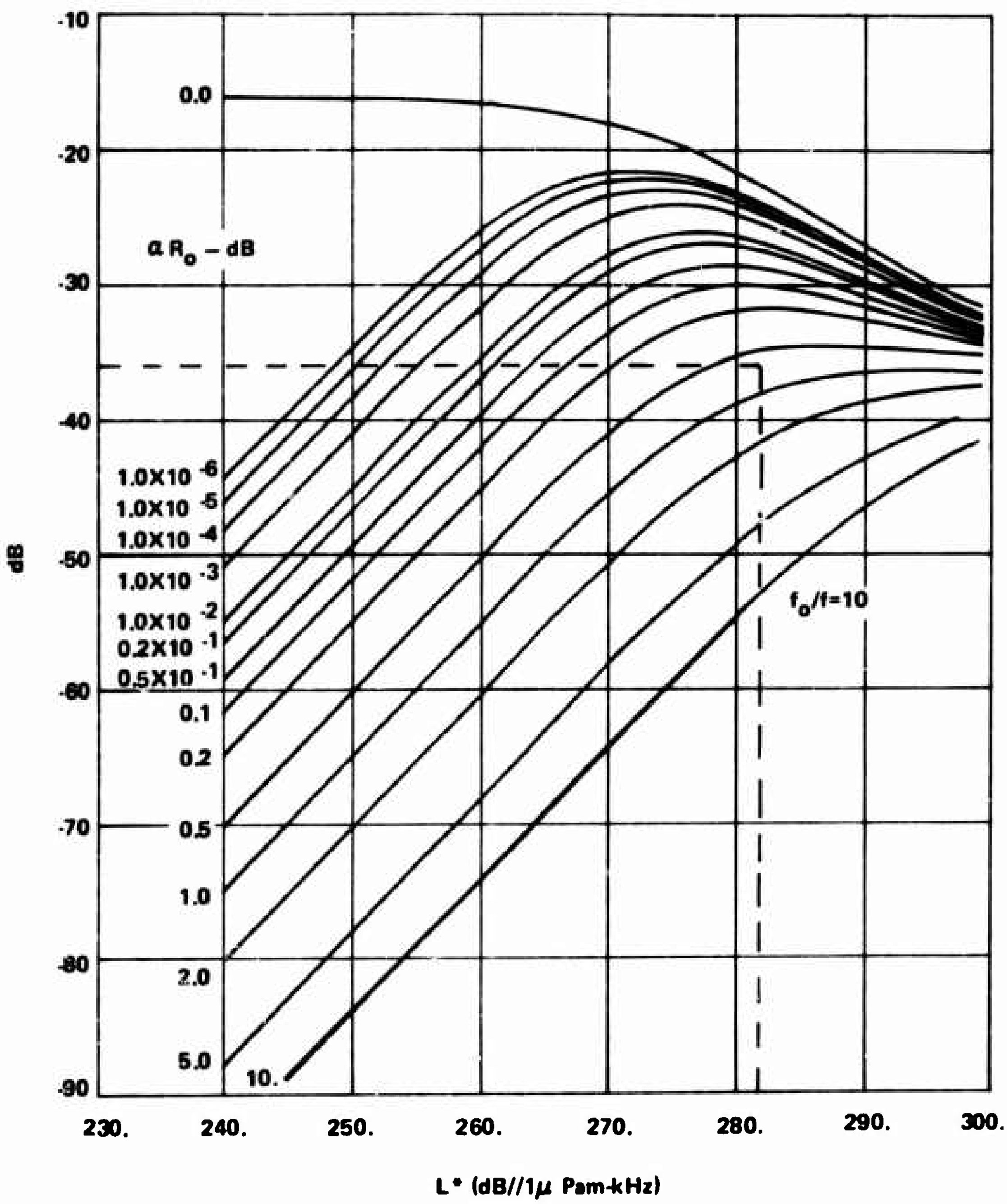

Figure 2. Source-Level Determination from Mellen-Moffett Model

parametric gain of -36 dB on the ordinate. Adding this gain to the primary source level per frequency (LSP) of 246 dB//1 μPam, we obtain a difference frequency source level of 210 dB//1 μPam at a difference frequency of 6.5 kHz (65/10).

To find the directivity index (NDI) and beamwidth at a difference frequency of 6.5 kHz, we enter figure 3 again at 282 dB//1 μPam-kHz, and reflect from the 0.6 point to find a DELTA NDI of -7 dB. The NDI of the 6.5-kHz difference frequency is then NDIP + ΔNDI, or 35 dB (42-7). The 3-dB or 6-dB beamwidth can be closely approximated by applying this NDI to a circular piston aperture. The 6-dB total beamwidth thus obtained is 4.7°.

The performance of the above source over the useful range of difference frequencies is shown in figure 4, with curves for source level and beamwidth labeled SOURCE 1. This source operating at the scaled source level of 282 dB is a nearfield, saturated radiator. At 14-kHz difference frequency, a source level of 222 dB can be realized with a 3-dB beamwidth of 2.8°.

It is interesting to compare this nearfield source with a predominantly farfield source, labeled SOURCE 2, whose parameters are listed above the curves. At a scaled source level of 256 dB, this source operates well below the 280-dB center of the broad turning point between the saturated and non-saturated source. Although of smaller diameter, this farfield source can provide higher source levels below 2 kHz with the same power input.

A word about the efficiency of the 0.9-m, 65-kHz source at 14-kHz difference frequency might be appropriate. To compare the parametric and conventional sources, we assume the same size projector, projector efficiency (50 percent), and on-axis source level for both parametric source and conventional source. The required power input to the conventional source on this basis would be about 400 watts. With a power input of 10 kW, this parametric source operates at 4 percent of the conventional source efficiency. Optimized parametric sources with stepdown ratios near 4 can achieve 10 percent source-level efficiency. It should be noted, however, that many practical parametric systems operate with efficiencies as low as 0.01 percent.

PROJECTOR DRIVE CONSIDERATIONS

Feed Techniques

Two basic arrangements are commonly used to achieve the collinear interaction of the two frequencies in the medium in front of the projector. The

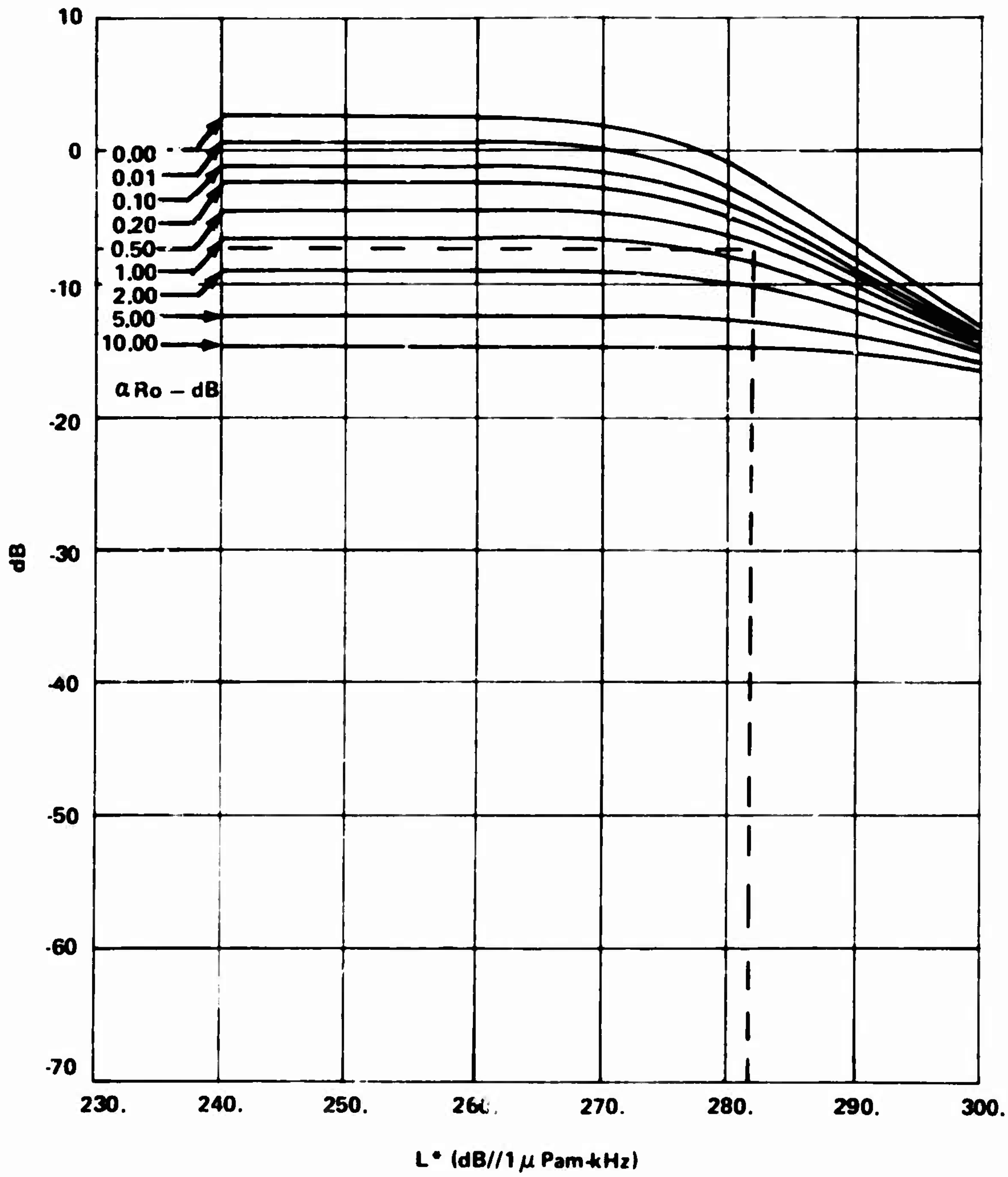

Figure 3. Directivity Determination from Mellen-Moffett Model

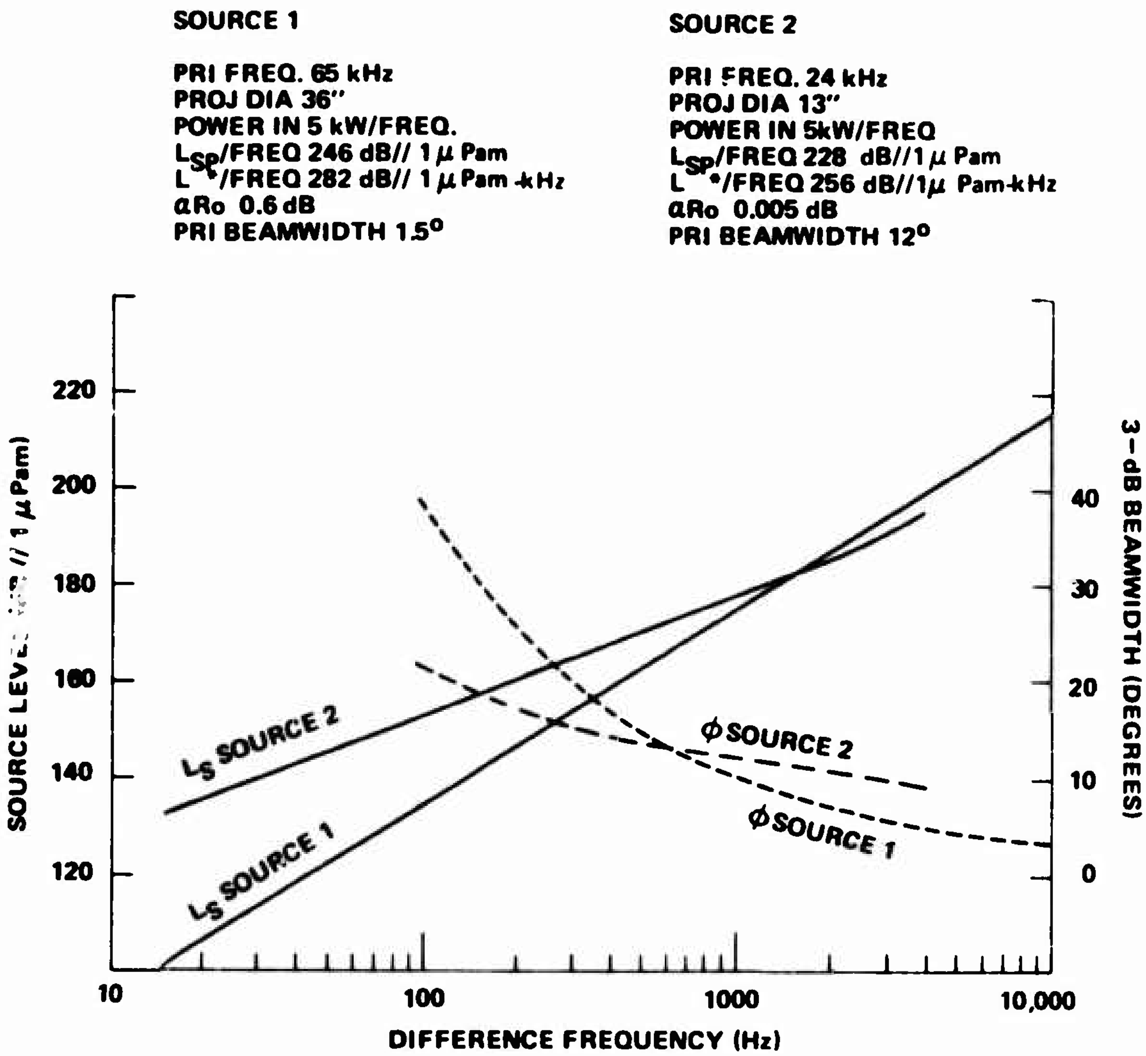

Figure 4. Performance Comparison of Nearfield and Farfield Sources

most common is to feed the primary frequencies through a common power amplifier and excite the entire projector. This technique is amenable to single element and multielement projectors and normally encounters no primary pattern problems. The disadvantages are that good amplifier linearity must be maintained, and a high-pass filter is usually required to prevent direct radiation of the difference frequency resulting from electronic intermodulation distortion. Also, the single driver must handle twice the average power because of the two-frequency waveform, and the projector must handle twice the voltage of one component.

The second technique is to checkerboard the elements in a multielement transducer and feed one primary frequency to the "red" elements and the other to the "black" elements through separate drivers. In practice, the checkerboard is randomized to prevent the formation of large, widely spaced sidelobes (grating lobes). Advantages of this feed are that no high-level filters are required, and higher amplifier distortion can be allowed. Unfortunately, the advantages — being able to handle the same average power with one-half the driver power capability and reducing the peak element voltage for the same power input — are largely wiped out by the increase in overall sidelobe level and loss of element efficiency. These problems arise because when the element size and spacing is the usual 1/2 wavelength (or slightly greater), the spacing between elements of the same frequency is 1 wavelength or greater. The array is then effectively a 50 percent thinned array at each frequency, and approximately half the total energy is lost to the sidelobes, compared to 15 percent in a full array. This is true no matter how cleverly the element arrangement is randomized. If element size can be reduced without appreciable efficiency loss, at least a portion of the power advantage of the checkerboard arrangement will be realized.

Projector Drive Waveforms.

Some studies have been made to examine the effect of the type of primary waveform or modulation on the efficiency of difference frequency generation. Careful measurements, using the 3-foot, 65-kHz source at a scaled source level of 276 dB and at a difference frequency of 2 kHz, show that for the same projector peak envelope voltage 100 percent AM (amplitude modulation) with sine-wave modulation gives about 1 dB more efficiency than the two-frequency case. Since the average power in the two-frequency waveform is 1.2 dB higher than the sine-wave AM for the same peak voltage, it appears that the AM sine wave gives about a 2.2-dB improvement in efficiency. Use of square-wave AM provides about 1-dB improvement over sine-wave AM. Difference frequency harmonics[3] at this drive level are greater with sine-wave

AM, and greater still with the square wave. This may be an advantage or a disadvantage, depending upon application.

DISTORTION IN PARAMETRIC SYSTEMS

Transmitting Systems.

The generation of unwanted frequency components can occur in the electronics or in the medium. Undesired second-order products (sum and difference of the primaries) are unavoidably generated in the power amplifier when amplifying two or more primary frequencies. The sum frequency can be ignored in most applications, since its frequency (and hence, its absorption) is high and its beam pattern is narrow. As stated previously, the difference frequency can be removed by a high-pass filter inserted between the driver and the projector. Higher even-order products, such as $2f_2 - 2f_1$ and $3f_2 - 2f_1 - f_3$ in the case of three primary frequencies, are removable by filtering. However, odd-order products such as $2f_1 - f_2$ and $2f_2 - f_1$ generated in the electronics cannot normally be removed by filtering, and can combine in the medium to produce frequencies close to the difference frequency. Fortunately, measurements to date indicate that the levels of electronically generated odd-order products are low compared with the unwanted components generated by the medium. Figure 5 illustrates the type of beam pattern resulting from direct radiation of the difference frequency. Generation of unwanted frequencies by the medium constitutes the main problem area of distortion in parametric sonar systems, particularly in systems where the difference-frequency band occupies more than one octave. Figure 6 illustrates the spectrum of components near the difference frequencies when three primary frequencies, 66, 67.8, and 68.9 kHz, are transmitted at the same amplitude. The 0.9-m projector described previously was used, and each primary component had a scaled source level of 272 dB//1 μPam-kHz. The desired frequencies of 1800 to 2900 kHz are 3 and 10 dB, respectively, above the highest undesired components. Compare this situation to that of figure 7, where the levels of the 67.8- and 68.9-kHz components (tone carriers) have been reduced 18 dB below the master carrier of 66 kHz while maintaining the same total peak drive voltage or acoustic pressure. Marked improvement in the ratio of the desired to the undesired components is obtained with only a 4- or 5-dB loss of desired source level. Thus, medium distortion can be controlled by adjustment of the relative levels of the primary components. It can be shown that for a given peak projector voltage the desired difference-frequency component levels are maximized when the pressure in the master carrier equals the sum of the pressures in the tone carriers.

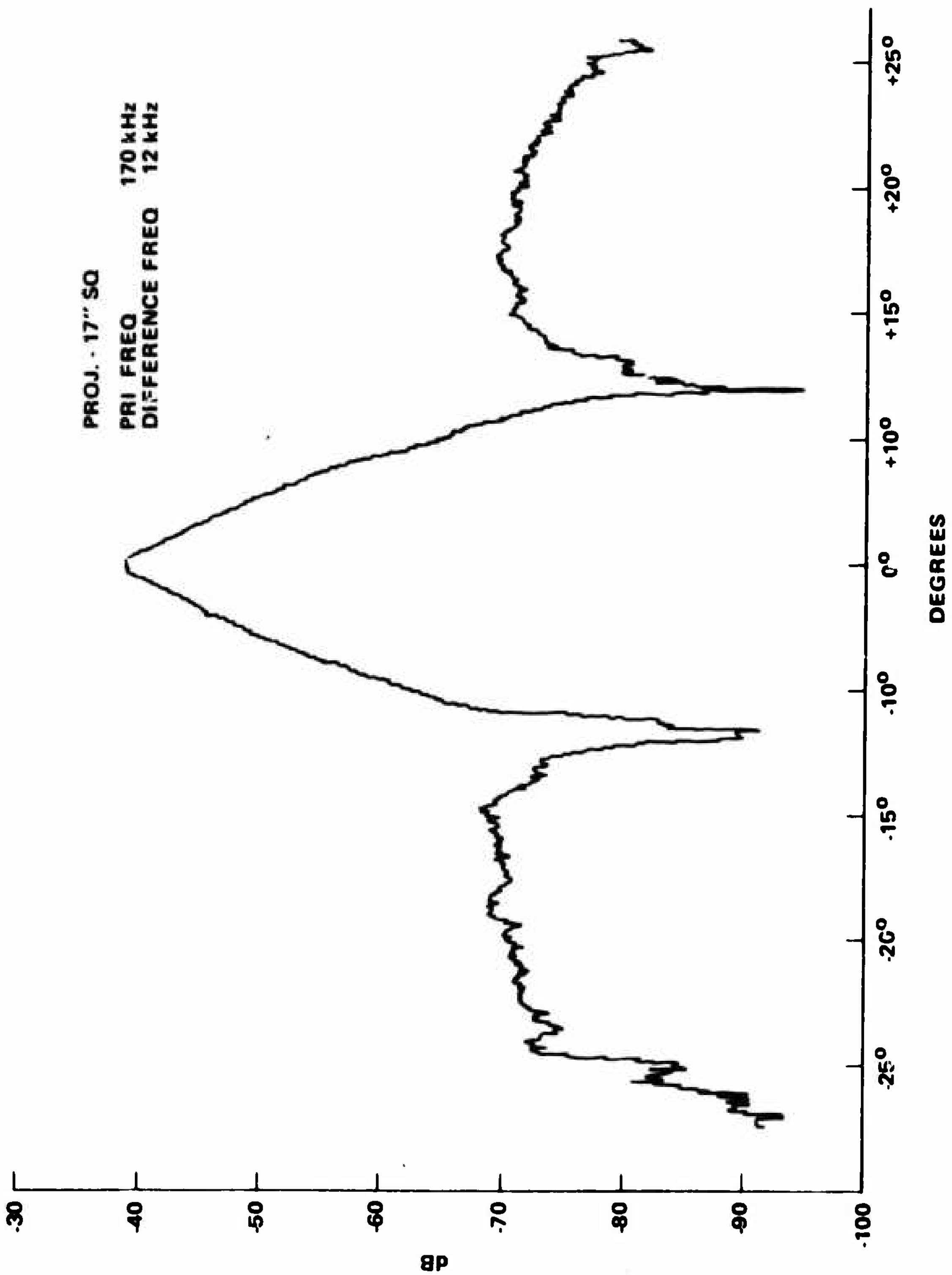

Figure 5. Effect of Direct Radiation on Parametric Pattern

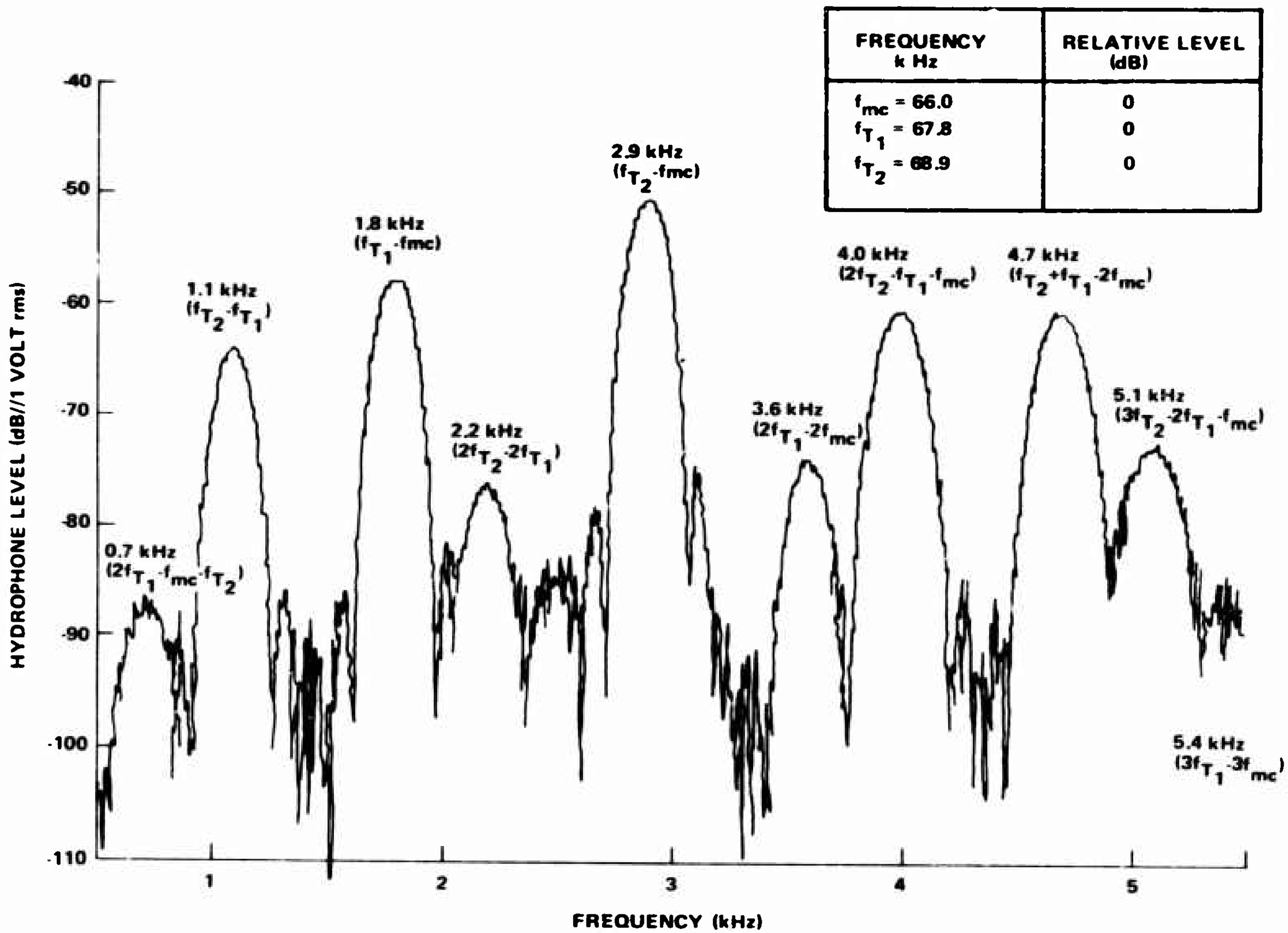

Figure 6. Components near Difference Frequencies, Three Primary Frequencies Transmitted Simultaneously

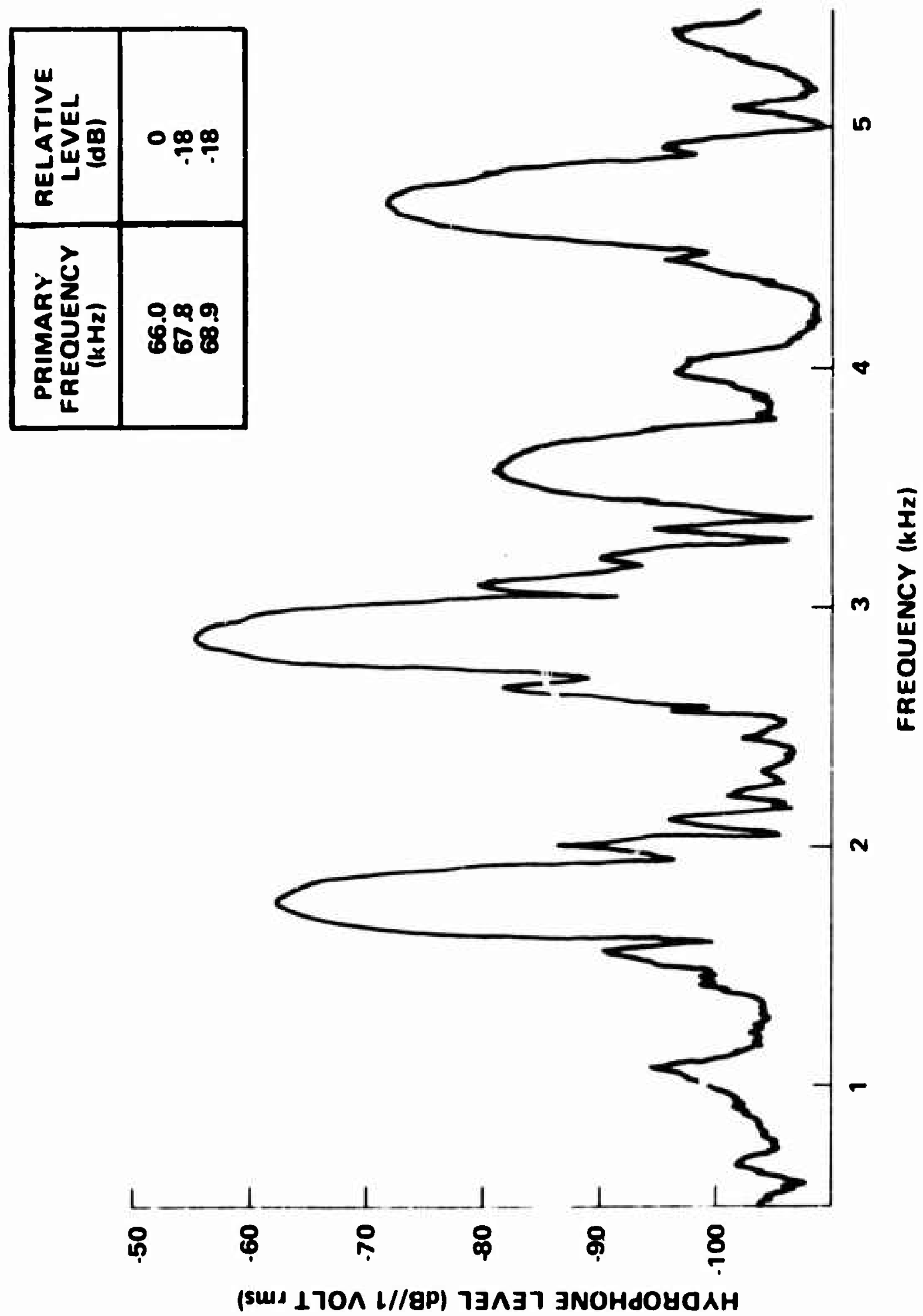

Figure 7. Components near Difference Frequencies, Tone Carriers Operating at Reduced Amplitude

Receiving System.

In many cases where measurements of the parametric source are to be made, large amounts of the primary frequencies reach the receiving hydrophone and related electronics. Two problems can result, the most common being overloading of the receiving amplifier system by the primary components. This results in generation of distortion products, notably the difference frequency, in the receiver. One means of detecting such distortion is by examination of the beam pattern, post-filtered at the difference frequency. The pattern will be similar to the primary pattern if the problem is present. A convenient and effective means of preventing this distortion is to include a low-pass RC filter of suitable impedance between the hydrophone and the electronics. Two cascaded sections will normally suffice.

The second receiver problem, less common but more annoying, is the distortion caused by the effects of radiation pressure (sometimes called pseudosound) on the hydrophone. This problem normally arises with very high ratios of the local primary-frequency pressure to the local difference-frequency pressure. This radiation pressure is the dc component of the acoustic field, and is therefore modulated strongly at the difference frequency. Distortion usually shows in the beam pattern where the top portion of the primary pattern will ride on top of the normal difference frequency pattern. Effects of radiation pressure can be reduced or eliminated by (1) increasing the projector-to-hydrophone-spacing (since the radiation pressure varies as the square of the local pressure); (2) trying a different hydrophone (since hydrophones react differently to radiation pressure); or (3) inserting an acoustic filter to attenuate the primaries. Such a filter should be inserted near the hydrophone so as not to affect difference frequency generation.

PERFORMANCE OF EXPERIMENTAL SYSTEMS

ACOUSTIC CALIBRATION SOURCE

The low-frequency limit of acoustic calibration facilities using conventional sources is determined primarily by the volume of water available. The narrow beam, short pulse length, and extended array length of the parametric source all serve to reduce boundary reflections and permit lower frequencies to be used in a given volume of water. Thus existing facilities can calibrate hydrophones to substantially lower frequencies using the parametric source. Experiments at NUSC's Millstone Facility have demonstrated a minimum usable frequency reduction from 400 to 100 Hz. [4]

Another study considered the parametric array for calibration of large sonar arrays.[5]

COMMUNICATIONS

The narrowbeam and broadband features of the parametric source are particularly advantageous in underwater acoustic communication systems. Narrow beams markedly reduce multipath distortion. Reduction in distortion and wide bandwidth allow transmission with very high data rates. In terms of percentage, the bandwidth of the parametric source is the transducer bandwidth at the primary frequencies multiplied by the stepdown ratio. Comparison tests between conventional and parametric sources transmitting voice and coded multitone formats demonstrate the marked reduction in multipath using the parametric source. Multitone rates of over 1600 bits/sec have been transmitted and successfully decoded over path lengths of 4000 yards.

The first parametric voice system, deployed by NUSC in 1972 to transmit speech between points in Long Island Sound, had the following characteristics:

Projector Diameter	10 in.
Primary Center Frequency (F_o)	250 kHz
Primary 3-dB Beamwidth	2°
Primary Source Level for each Frequency	237 dB//1 μPam
Power Input for each Frequency	2 kW
Difference Frequency	8-11 kHz
Difference-Frequency Source Level	190 dB//1 μPam
Difference-Frequency, 3-dB Beamwidth	4°

Figure 8 shows the midband difference-frequency beam pattern of the source.

ECHO RANGING

Successful echo ranging of submarines or other targets requires relatively high source levels: over 210 dB//1 μPam is usually necessary. Like similar developments, the early parametric sources could not provide the levels required for real-world echo ranging. Several parametric sources have now been designed, built and tested that are capable of target echo ranging. The 0.9m, 65-kHz system described previously, with its 222 dB//1 μPam level at 14 kHz, has successfully echo ranged at substantial ranges.

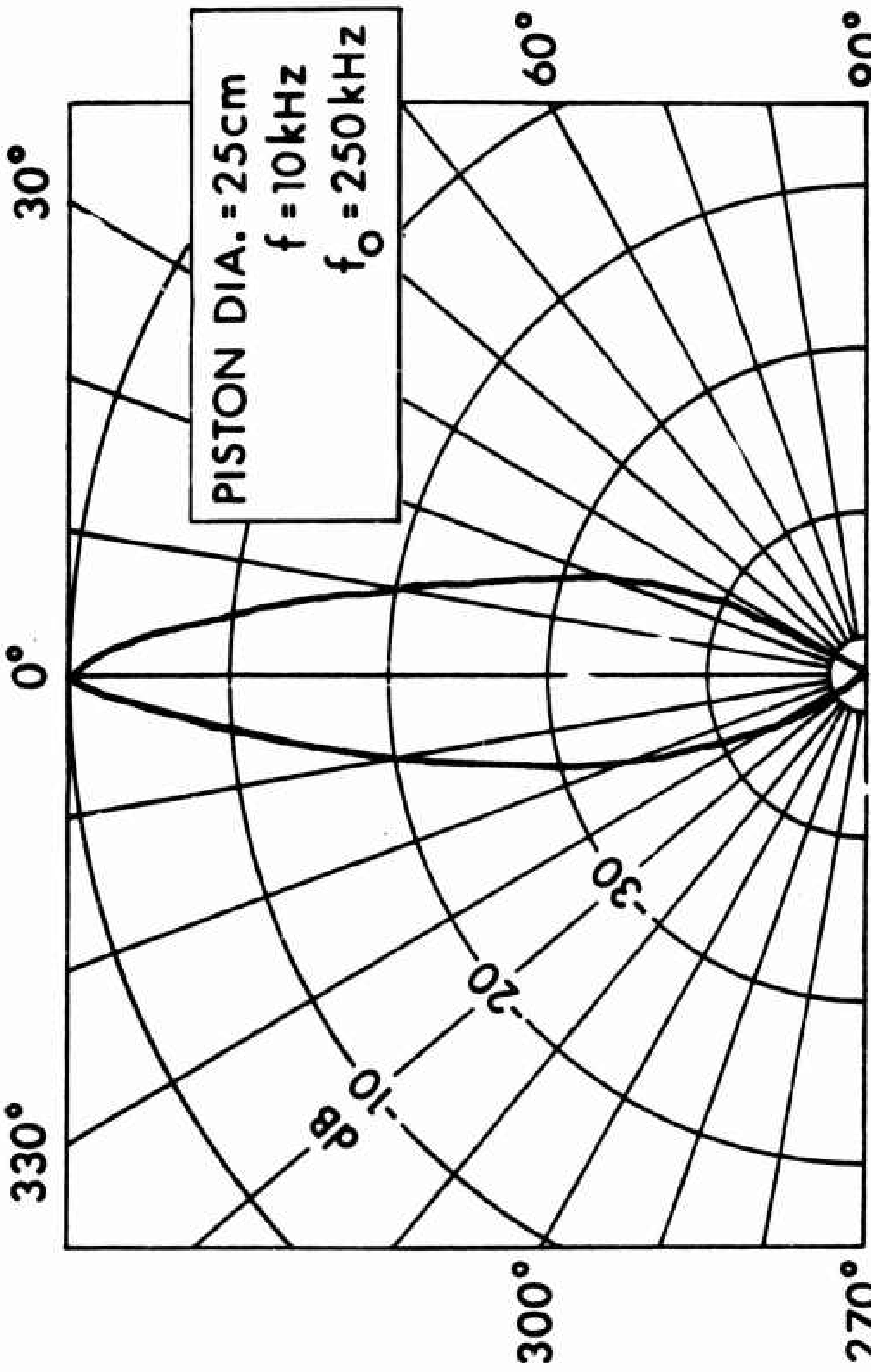

Figure 8. Parametric Directivity Pattern

The characteristics of a high-power source called the TOPS (for TOwed Parametric Sonar) are shown in Table 1. This source has also been used for target echo ranging at difference frequencies of 2 and 4 kHz.

Table 1. TOPS Performance

Projector Size	76 in. x 21 in.
Primary Mean Frequency	23 kHz
Projector Power Input for each Frequency	40 kW

Difference Frequency (Hz)	Source Level (dB//1 µPam)
5000	230
2500	222
1000	209
500	198
250	186
100	173
50	162

Model studies, in some cases substantiated by experiment, have demonstrated that under many reverberation-limited situations the narrow pattern gives the parametric source a distinct advantage over the conventional. Under some conditions, the very short pulse capabilities of the parametric source provide further discrimination against reverberation.

BOTTOM AND SUB-BOTTOM PROFILING

The parametric source has proven to be very useful for high-resolution bottom and sub-bottom profiling. Its primary advantage for shallow bottom profiling is the capability of emitting very short, clean pulses. An example of such is shown in figure 9. In deeper water where absorption becomes important, the narrow low-frequency beam achievable from a projector of small size also makes the parametric source advantageous.

For sub-bottom profiling, the parametric source can achieve performance unattainable by the conventional source. First, the parametric source allows sub-bottom echos free of interference resulting from bottom-reflected side lobes arriving at the same time as the desired sub-bottom returns. In an early

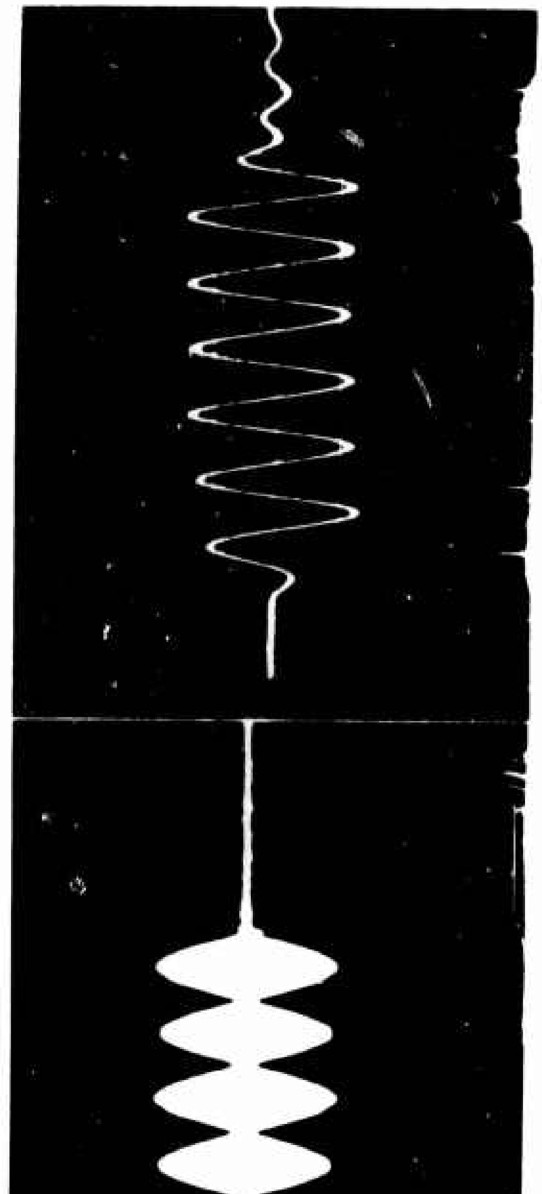

Figure 9. Sample Pulses from Parametric Source

test, sub-bottom returns were obtained in 8 feet of water beside a stone dock. Second, the ability to generate low frequencies having narrow beamwidths from practical-size projectors cannot be duplicated by the conventional source. Here, relatively low frequencies are required to attain desired bottom penetration.

Sub-bottom penetration of 250 feet in 500 feet of water at Seneca Lake has been achieved with the 0.9-m, 65-kHz source at a difference frequency of 3.5 kHz.[6] The TOPS projector has demonstrated 300-foot penetration in 15,000 feet of water 50 miles north of Eleuthera, Bahamas, using a difference frequency of 2 kHz.[7] Excellent sub-bottom results were obtained with the TOPS projector over the frequency range from 1 to 6 kHz.

Good side-scan results have also been obtained with the TOPS source. In tests in 3600 feet of water near Catalina, bottom widths of over 1000 meters were illuminated.

Some work has been done using the parametric source for deep scattering layer investigations.[8] In these experiments the 3-foot, 65-kHz projector that served as the parametric source showed better resolution of fish targets near the surface than did a conventional system.

THE CAVITATING PARAMETRIC SOURCE

It has been demonstrated that when the primary frequencies are mixed in the presence of bubbles, the efficiency of difference-frequency generation is increased by orders of magnitude. The techniques can be divided into three types: self-cavitation, separate cavitation, and gas bubble injection. In the self-cavitation technique[9] the two primary waves themselves produce the necessary cavitation. Operating face pressure, frequencies, pulse length and depth must be such that cavitation can occur. A 31-cm projector at a mean primary frequency of 25 kHz and a face pressure of 243 dB//1 μPa was used. At 4-kHz difference frequency, the efficiency increased 34 dB when the projector was raised from a non-cavitating to a cavitating depth. The beam pattern changed from the typical narrow parametric to an essentially omnidirectional pattern as the depth decreased.

Experiments using separate cavitation also demonstrated a large increase in efficiency. In one case, the non-cavitating two-frequency beam was focused through a ceramic ring projector fed with a lower frequency at such a level as to produce cavitation inside the ring.[10]

In a third experiment a bubble screen was inserted between the two-frequency source and the hydrophone.[11] When the bubble screen was on, increases of 25 to 30 dB in the difference-frequency pressure level were noted at the hydrophone.

Although cavitating parametric sources are in an early stage of development, some applications appear promising. The cavitating source appears competitive with the broadband low-frequency projector from the standpoint of efficiency and allows the use of more rugged and simpler high-frequency projectors.

PARAMETRIC RECEIVING EXPERIMENTS

Many parametric receiving experiments have been performed, most on a relatively small scale. An experiment conducted by NUSC[12] used equipment with the following parameters:

Pump projector diameter	4 in.
Pump frequency	620 kHz
Pump source level	240 dB//1 μPam (max)
Array length	5.3 m and 9.1 m
Signal frequency	44 kHz

The beam patterns shown in figures 10 and 11 agree well with theory and show the effect of changing pump amplitude. Note the effect of pump saturation. Array gain, i.e., level of the up-converted sideband to level of signal frequency received directly, was -2.9 dB for the 5.6-m and -1.5 dB for the 9.1-m array length at a pump level of 240 dB//1 μPam in both cases. The most extensive work on parametric receiving arrays has been done by H. O. Berktay[13] and personnel of the Applied Research Laboratory, the University of Texas, Austin.[14]

CONCLUSIONS AND RECOMMENDATIONS

The parametric difference-frequency acoustic source has proven its advantages over conventional sources for high-resolution bottom and sub-bottom profiling, for communications, and for high-resolution sonar (particularly for shallow water applications). There are, however, many areas of nonlinear technology where further work with parametric sources promises to pay off in new or improved systems.

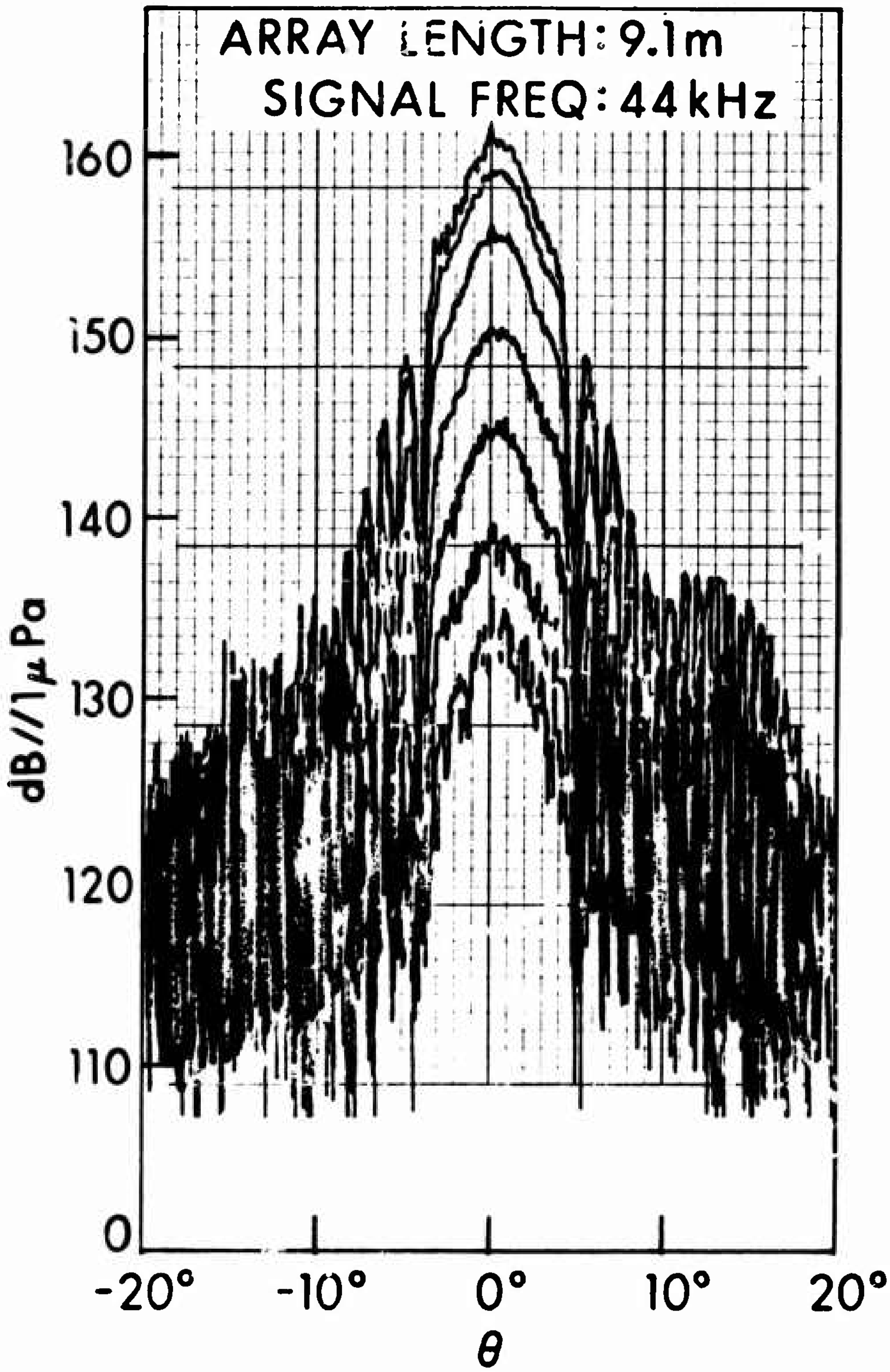

Figure 10. Receiving Beam Patterns, 9.1-m Array

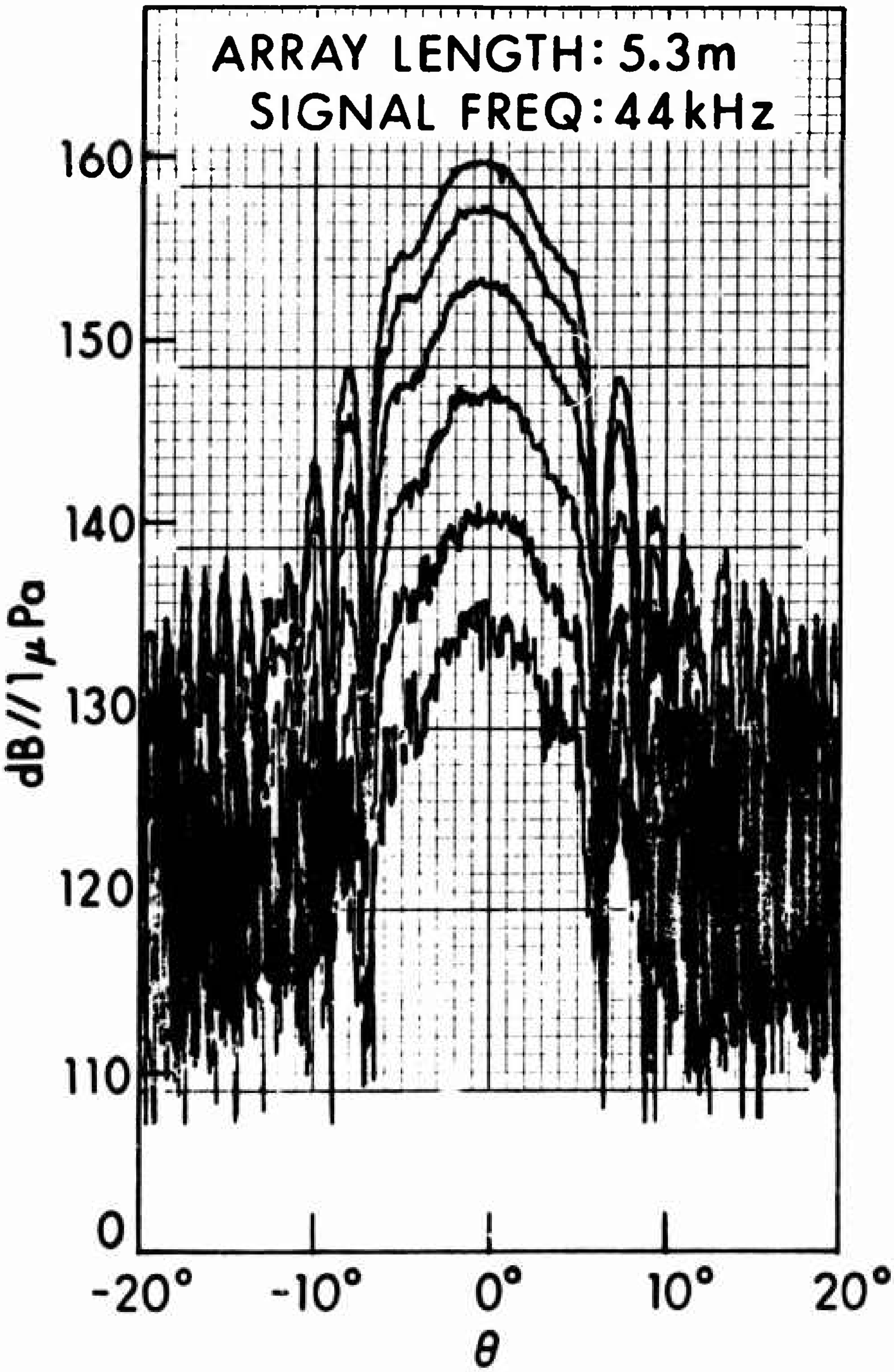

Figure 11. Receiving Beam Patterns, 5.6-m Array

Engineering design techniques for parametric difference-frequency sources employing circular and rectangular transducers of low aspect ratios (ratios of length to width) are well developed, notably via the Mellen-Moffett model. The usefulness of this model has been verified by experimental work covering a wide range of primary frequencies, projector sizes, and difference frequencies. Further theoretical and experimental work is needed, however, to extend the model to the design of parametric sources with transducers of high aspect ratios, particularly where saturation effects must be considered. The NUSC TOPS transducer (0.5m x 2m) and other rectangular transducers contemplated for future systems require an accurate model of their difference-frequency source level and beam patterns.

Optimizing projector drive technique for parametric sources will require further investigations to determine whether the better method is to drive all elements at both primary frequencies or to "checkerboard" elements by driving two groups of elements, one at each frequency. Intimately associated with this problem is the selection of element size and driver operating modes. Switching drivers are particularly attractive in light of the high input power required by many parametric sources.

Cavitating parametric sources hold promise for the development of rugged low-frequency omni- or broadly directional sources. The greater efficiency of the cavitating source makes it competitive with conventional broadband low-frequency sources. Full exploitation of the cavitating source will require a theoretical and experimental program of study.

While the conventional parametric receiver is well understood and its design routine, much work remains before its advantages and limitations are fully known. In particular, the low-frequency characteristics of the parametric receiver are critically dependent on pump spectral purity and on receiver noise and bandwidth. These relationships also deserve further study.

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